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HYPERON POLARIZATION IN THE CONSTITUENT QUARK MODEL

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Abstract

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We consider a mechanism for hyperon polarization in the inclusive production. The main role belongs to the orbital angular momentum and polarization of strange quark-antiquark pairs in the internal structure of constituent quarks. We treat a nucleon as a core consisting of the constituent quarks embedded into a quark condensate. The nonperturbative hadron structure is based on the results of chiral quark models.

Аннотация

Трошин С.М., Тюрин Н.Е. Поляризация гиперонов в модели составляющих кварков: Препринт ИФВЭ 96-12. – Протвино, 1996. – 14 с., 2 рис., библиогр.: 28.

Рассматривается возможный механизм возникновения поляризации гиперонов в инклюзивном рождении. Основную роль в этом механизме играет орбитальный момент пар странных кварков, присутствующих внутри составляющих кварков. Структура нуклона при этом основана на выводах моделей киральных кварков, учитывающих непертурбативные эффекты.

Introduction

One of the most puzzling and persistent, since long ago, spin effects was observed in inclusive hyperon production in collisions of unpolarized hadron beams. A very significant polarization of Λ–hyperons was discovered two decades ago [1]. Since then measurements in different processes have been performed [2] and a number of models has been proposed for a qualitative and quantitative description of these data [3]. Among them is the Lund model based on the classical string mechanism of strange quark pair production [4], the models based on spin–orbital interaction [5] and multiple scattering of massive strange sea quarks in effective external field [6] and also the models for polarization of Λ in diffractive processes with account for proton states with additional $\bar{s}s$ pairs such as $|uud\bar{s}s\rangle$ [7,8]. Besides it was proposed to connect Λ polarization in the process $pp \to \Lambda X$ with the polarization in the process $\pi p \to \Lambda K$ [9] and use triple Regge approach [10].

The mechanism of gluon fusion in the perturbative QCD as a source of strange quark polarization has been considered in [11] and x and $p_\perp$–dependencies of Λ–polarization has been discussed.

Nevertheless, hyperon polarization phenomena are not completely understood in QCD and currently could be considered even as a more serious problem than the problem of proton spin which hopefully will find its final resolution in the near future. Of course, those problems are interrelated and one could attempt to connect the spin structure of nucleons studied in deep–inelastic scattering with the polarization of Λ's observed in hadron production. As it is widely known now, only part (less than one third in fact) of the proton spin is due to quark spins [12,13]. These results can be interpreted in the effective QCD approach ascribing a substantial part of hadron spin to an orbital angular momentum of quark matter. It is natural to guess that this orbital angular momentum might be revealed in asymmetries in hadron production.

It is also evident from deep–inelastic scattering data [12,13,14] that strange quarks play an essential role in the proton structure and in its spin balance in particular. They are negatively polarized in a polarized nucleon, $\Delta s \simeq -0.1$. Polarization effects in hyperon production also continue demonstrating [2] that strange quarks produced in hadron interactions appear to be polarized.

In the recent papers [15] we considered a possible origin of asymmetry in the pion and φ–meson production under collision of a polarized proton beam with unpolarized proton target and argued that the orbital angular momentum of partons inside constituent quarks led to significant asymmetries in meson production. In this paper we consider how the most characteristic features of hyperon and first of all Λ polarization can be accounted in such approach.

1. Structure of constituent quarks

We consider a nonperturbative hadron as consisting of the constituent quarks located at the central part of the hadron which is embedded into a quark condensate. Experimental and theoretical arguments in favor of such a picture were given, e.g. in [16,17]. We refer to the effective QCD and use the NJL model [18] as a basis. The Lagrangian in addition to the four–fermion interaction of the original NJL model includes the six–fermion $U(1)_A$–breaking term.

Transition to a partonic picture in this model is described by the introduction of a momentum cutoff $\Lambda = \Lambda_\chi \simeq 1$ GeV, which corresponds to the scale of chiral symmetry spontaneous breaking. We adopt the point that the need for such cutoff is an effective implementation of the short distance behaviour in QCD [19].

The constituent quark masses can be expressed in terms of quark condensates [19], e.g.

$$m_U = m_u - 2g_4\langle 0|\bar{u}u|0\rangle - 2g_6\langle 0|\bar{d}d|0\rangle\langle 0|\bar{s}s|0\rangle. \tag{1}$$

In this approach massive quarks appear as quasiparticles, i.e. as current quarks and the surrounding clouds of quark–antiquark pairs which consist of a mixture of quarks of the different flavors. It is worth to stress that in addition to u and d quarks a constituent quark (U, for example) contains pairs of strange quarks (cf. Eq. (1)). The quantum numbers of constituent quarks are the same as the quantum numbers of current quarks due to the conservation of the corresponding currents in QCD. The only exception is the flavor–singlet, axial–vector current, it has a Q^2–dependence due to an axial anomaly which arises under quantization.

Quark radii are determined by the radii of the clouds surrounding it. We assume that the strong interaction radius of quark Q is determined by its Compton wavelength: $r_Q = \xi/m_Q$, where constant ξ is universal for different flavors. Quark formfactor $F_Q(q)$ is taken in the dipole form, viz

$$F_Q(q) \simeq (1 + \xi^2\vec{q}^{\,2}/m_Q^2)^{-2} \tag{2}$$

and the corresponding quark matter distribution $d_Q(b)$ is of form [17]:

$$d_Q(b) \propto \exp(-m_Q b/\xi). \tag{3}$$

A spin of the constituent quark J_U in this approach is given by the following sum

$$J_U = 1/2 = J_{u_v} + J_{\{\bar{q}q\}} + \langle L_{\{\bar{q}q\}}\rangle = 1/2 + J_{\{\bar{q}q\}} + \langle L_{\{\bar{q}q\}}\rangle. \quad (4)$$

The value of the orbital momentum contribution into the spin of constituent quark can be estimated with account for the new experimental results from deep–inelastic scattering [14] indicating that quarks carry even less than one third of proton spin, i.e.

$$(\Delta\Sigma)_p \simeq 0.2,$$

and taking into account the relation between contributions of current quarks into a proton spin and the corresponding contributions of current quarks into a spin of constituent quarks and that of constituent quarks into proton spin [13]:

$$(\Delta\Sigma)_p = (\Delta U + \Delta D)(\Delta\Sigma)_U. \quad (5)$$

If we adopt that $\Delta U + \Delta D = 1$[1] then we should conclude that $J_{u_v} + J_{\{\bar{q}q\}} = 1/2(\Delta\Sigma)_U \simeq 0.1$ and from Eq. (4) $\langle L_{\{\bar{q}q\}}\rangle \simeq 0.4$, i. e. about 80% of the U or D-quark spin is due to the orbital angular momenta of u, d and s quarks inside the constituent quark while the spin of current valence quark is screened by the spins of the quark–antiquark pairs. It is also important to note the exact compensation between the spins quark–antiquark pairs and their angular orbital momenta:

$$\langle L_{\{\bar{q}q\}}\rangle = -J_{\{\bar{q}q\}}. \quad (6)$$

Since we consider the effective Lagrangian approach where gluon degrees of freedom are overintegrated, we do not discuss problems of the principal separation and mixing of the quark orbital angular momentum and gluon effects in QCD (cf. [21]). In the NJL–model [19] the six-quark fermion operator simulates the effect of gluon operator $\frac{\alpha_s}{2\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$, where $G_{\mu\nu}$ is the gluon field tensor in QCD. The only effective degrees of freedom here are quasiparticles; mesons and baryons are the bound states arising due to residual interactions between the quasiparticles.

An account for axial anomaly in the framework of chiral quark models results in a compensation of the valence quark helicity by helicities of quarks from the cloud in the structure of constituent quark. The specific nonperturbative mechanism of such compensation differs for different approaches [19,22], e.g. the modification of the axial U(1) charge of constituent quark is considered to be generated by the interaction of current quarks with flavor singlet field φ^0. The apparent physical mechanism of such compensation has been discussed recently in [8].

On these grounds we can conclude that a significant part of the spin of constituent quark should be associated with the orbital angular momentum of quarks inside this

[1] We will use this simplest assumption, which is enough for our estimates. However, the account of orbital and gluonic effects at the level of constituent quarks reduces $\Delta U + \Delta D$ by 25% [20,21].

constituent quark, i.e. the cloud quarks should rotate coherently inside a constituent quark.

The important point what the origin of this orbital angular momentum is. It was proposed [15] to use an analogy with an anisotropic extension of the theory of superconductivity which seems to match well the above picture for a constituent quark. The studies [23] of that theory show that the presence of anisotropy leads to axial symmetry of pairing correlations around the anisotropy direction $\hat{\vec{l}}$ and to the particle currents induced by the pairing correlations. In other words it means that a particle of the condensed fluid is surrounded by a cloud of correlated particles ("hump") which rotate around it with the axis of rotation $\hat{\vec{l}}$. (cf. Eq. (4)). The calculation of the orbital momentum shows that it is proportional to the density of the correlated particles. Thus, it is clear that there is a direct analogy between this picture and that describing the constituent quark. An axis of anisotropy $\hat{\vec{l}}$ can be associated with the polarization vector of valence quark located at the origin of the constituent quark. The orbital angular momentum $\vec{L}$ lies along $\hat{\vec{l}}$ (cf. Eq. (4)).

We argued that the existence of this orbital angular momentum, i.e. the orbital motion of quark matter inside a constituent quark, is the origin of the observed asymmetries in inclusive production at moderate and high transverse momenta. Indeed, since the constituent quark has a small size

$$r_Q = \xi/m_Q, \quad \xi \simeq 1/3, \quad m_Q \propto -\langle 0|\bar{q}q|0\rangle/\Lambda_\chi^2$$

the asymmetry associated with internal structure of this quark will be significant at $p_\perp > \Lambda_\chi \simeq 1$ GeV/c where interactions at short distances give a noticeable contribution.

The behaviour of asymmetries in inclusive meson production was predicted [15] to have a corresponding $p_\perp$ – dependence, in particular, vanishing asymmetry at $p_\perp < \Lambda_\chi$, its increase in the region of $p_\perp \simeq \Lambda_\chi$, and $p_\perp$ – independent asymmetry at $p_\perp > \Lambda_\chi$. The parameter $\Lambda_\chi \simeq 1$ GeV/c is determined by the scale of chiral symmetry spontaneous breaking. Such a behaviour of asymmetry follows from the fact that the constituent quarks themselves have slow (if at all) orbital motion and are in the S–state, but interactions with $p_\perp > \Lambda_\chi$ resolve the internal structure of constituent quark and "feel" the presence of internal orbital momenta inside this constituent quark.

It should be noted that at high $p_\perp$ we will see the constituent quark being a cluster of partons which, however, should preserve their orbital momenta, i.e. the orbital angular momentum will be retained and the partons in the cluster are to be correlated. It should be stressed again that a nonzero internal orbital momentum of partons in the constituent quark means that there are significant multiparton correlations. The presence of such parton correlations is in agreement with a high locality of strange sea in the nucleon. The concept of locality was proposed in [24] on the basis of analysis of the recent CCFR data [25] for neutrino deep–inelastic scattering. The locality serves as a measure for the local proximity of strange quark and antiquark in momentum and coordinate spaces. The CCFR data were shown [24] to indicate that the strange quark and antiquark had very similar distributions in momentum and coordinate spaces.

2. Model for Λ–hyperon polarization

We consider the hadron process of the type

$$h_1 + h_2 \to h_3^\uparrow + X$$

with an unpolarized beam and target. Usually we consider h_1 and h_2 being protons and h_3 — Λ–hyperon. Its polarization is being measured through the angular distribution of products in the parity nonconserving Λ decay.

The picture of a hadron consisting of constituent quarks embedded into quark condensate implies that the overlapping and interaction of peripheral clouds occur at the first stage of hadron interaction. Under this, condensate is being excited and as a result the quasiparticles , i. e. massive quarks, appear in the overlapping region. It should be noted that the condensate excitations are massive quarks, since the vacuum is nonperturbative one and there is no overlapping between the physical (nonperturbative) and bare (perturbative) vacuum [16,18]. The part of hadron energy carried by the outer clouds of condensates being released in the overlapping region, goes to the generation of massive quarks. The number of such quarks fluctuates. The average number of these quarks in the framework of the geometrical picture can be estimated as follows:

$$N(s,b) \propto N(s) \cdot D_c^{h_1} \otimes D_c^{h_2}. \tag{7}$$

Sign ⊗ denotes the convolution integral

$$\int D_c^{h_1}(\vec{b}')D_c^{h_2}(\vec{b}-\vec{b}')d^2\vec{b}'.$$

The function $D_c^{h_i}$ describes the condensate distribution inside hadron h_i and b is the impact parameter of colliding hadrons h_1 and h_2. To estimate the function $N(s)$ we can use the maximal possible value $N(s) \propto \sqrt{s}$ [17]. Thus, as a result massive virtual quarks appear in the overlapping region and some mean field is generated.

Constituent quarks located in the central part of hadron are supposed to scatter in a quasi-independent way by this mean field.

We propose the following mechanism for polarization of Λ–hyperons based on the above picture for hadron structure. An inclusive production of the hyperon h_3 results from two mechanisms: recombination of the constituent quarks with virtual massive strange quark (low $p_\perp$'s, soft interactions) into h_3 hyperon or from the scattering of a constituent quark in the mean field, excitation of this constituent quark, the appearence of a strange quark as a result of decay of the constituent quark and the subsequent fragmentation of strange quark in the hyperon h_3. The second mechanism is determined by the interactions at distances smaller than constituent quark radius and is associated therefore with hard interactions (high $p_\perp$'s). This second mechanism could result from the single scattering in the mean field, excitation and decay of constituent quark or from the multiple scattering in this field with subsequent corresponding excitation and decay of the constituent quark. It is due to the multiple scattering by mean field that the parent constituent quark becomes polarized since it has a nonzero mass [6] and this polarization results in polarization of produced strange quarks and the appearance of the corresponding angular orbital momentum. Other mentioned mechanisms lead to the production of unpolarized Λ–hyperons. Thus, we adopt a two–component picture of hadron production which incorporates interactions at long and short distances and it is the short distance dynamics that determines the production of polarized Λ–hyperon.

It is necessary to note here, that after the decay of the parent constituent quark, current quarks appear in the nonperturbative vacuum and become a quasiparticles due to the nonperturbative dressing with a cloud of $\bar{q}q$-pairs. A mechanism of this process could be associated with the strong coupling existing in the pseudoscalar channel [8,19].

Now we write down the explicit formulas for the corresponding inclusive cross–sections and polarization of hyperon h_3. The following expressions were obtained in [26] which take into account the unitarity in the direct channel of reaction. They have the form

$$\frac{d\sigma^{\uparrow,\downarrow}}{d\xi} = 8\pi \int_0^\infty bdb \frac{I^{\uparrow,\downarrow}(s,b,\xi)}{|1-iU(s,b)|^2}, \tag{8}$$

where b is the impact parameter of colliding hadrons. Here function $U(s,b)$ is the generalized reaction matrix (helicity nonflip one) which is determined by dynamics of the elastic reaction

$$h_1 + h_2 \to h_1 + h_2.$$

The arrows here denote the corresponding transverse polarization of hyperon h_3.

The functions $I^{\uparrow,\downarrow}(s,b,\xi)$ are related to the functions $U_n(s,b,\xi,\{\xi_{n-1}\})$ which are the multiparticle analogs of the $U(s,b)$ and are determined by dynamics of the exclusive processes

$$h_1 + h_2 \to h_3^{\uparrow,\downarrow} + X_{n-1}.$$

The kinematical variables ξ (x and $p_\perp$, for example) describe the kinematical variables of the produced hyperon h_3 and a set of variables $\{\xi_{n-1}\}$ describes the system X_{n-1} of $n-1$ particles. It is useful to introduce the two functions I_+ and I_-:

$$I_\pm(s,b,\xi) = I^\uparrow(s,b,\xi) \pm I^\downarrow(s,b,\xi), \tag{9}$$

where $I_+(s,b,\xi)$ corresponds to an unpolarized case. The following sum rule takes place for the function $I_+(s,b,\xi)$:

$$\int I_+(s,b,\xi)d\xi = \bar{n}(s,b)\mathrm{Im}U(s,b), \tag{10}$$

where $\bar{n}(s,b)$ is the mean multiplicity of secondary particles in the impact parameter representation.

Polarization P defined as the ratio

$$P(s,\xi) = \{\frac{d\sigma^\uparrow}{d\xi} - \frac{d\sigma^\downarrow}{d\xi}\}/\{\frac{d\sigma^\uparrow}{d\xi} + \frac{d\sigma^\downarrow}{d\xi}\}$$

can be expressed in terms of the functions $I_\pm$ and U:

$$P(s,\xi) = \int_0^\infty bdbI_-(s,b,\xi)/|1-iU(s,b)|^2/\int_0^\infty bdbI_+(s,b,\xi)/|1-iU(s,b)|^2. \tag{11}$$

Using relations between transversely polarized states $|\uparrow,\downarrow\rangle$ and helicity states $|\pm\rangle$, one can write down expressions for I_+ and I_- through the helicity functions $U_{\{\lambda_i\}}$:

$$I_+(s,b,\xi) = \sum_{n,\lambda_1,\lambda_2,\lambda_3,\lambda_{X_{n-1}}} n\int d\Gamma'_n |U_{n,\lambda_1,\lambda_2,\lambda_3,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\})|^2, \tag{12}$$

$$I_-(s,b,\xi) = \sum_{n,\lambda_1,\lambda_2,\lambda_{X_{n-1}}} 2n\int d\Gamma_{n-1}\mathrm{Im}[U_{n,\lambda_1,\lambda_2,+,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\}) \\ U^*_{n,\lambda_1,\lambda_2,-,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\})]. \tag{13}$$

Here the $\lambda_{X_{n-1}}$ denotes the set of helicities of particles from X_{n-1} system; note that in general this system as a whole has no definite spin or helicity.

Since in the model constituent quarks are quasi–independent ones and the production of hyperon h_3 is the result of interaction of one of them with the mean field, we can write the helicity functions $U_{\{\lambda_i\}}$ as a sum $U_{\{\lambda_i\}} = \sum_j U^{Q_j}_{\{\lambda_i\}}$ or simply as $U_{\{\lambda_i\}} = NU^Q_{\{\lambda_i\}}$ taking into account that there are no constituent strange quarks among the N initial quarks in the colliding hadrons h_1 and h_2 (we do not consider here the processes with initial hadrons containing strange quarks and therefore all the constituent quarks are considered to be equivalent in respect to the production of the hyperon h_3). The superscript Q denotes that the helicity function $U^Q_{\{\lambda_i\}}$ describes the production of hyperon h_3 as a result of interaction of a quark Q with the mean field.

In the model the spin–independent part $I^Q_+(s,b,\xi)$ (note that $I_\pm(s,b,\xi) = N^2 I^Q_\pm(s,b,\xi)$) gets a contribution from the processes at small (hard processes) as well as at large (soft processes) distances, i.e.

$$I^Q_+(s,b,\xi) = I^{hQ}_+(s,b,\xi) + I^{sQ}_+(s,b,\xi),$$

while the spin–dependent part $I^Q_-(s,b,\xi)$ gets a contribution from the interactions at short distances only

$$I^Q_-(s,b,\xi) = I^{hQ}_-(s,b,\xi).$$

The presence of internal orbital momenta in the structure of constituent quark will lead to a certain shift in the transverse momenta of produced hyperon, i.e. $p_\perp \to p_\perp \pm k_\perp$. We suppose on the basis of Eq. (6) that there is a particular flavor compensation between spin and orbital momentum of strange quarks inside constituent quarks, i.e.

$$L_{s/Q} = -J_{s/Q}. \tag{14}$$

It seems to be a natural assumption and due to this the effect of shift of transverse momenta and polarization of Λ–hyperon are directly connected since the spin and polarization of Λ–hyperon are completely determined by those of the strange quarks in the simple $SU(6)$ scheme. Eq. (14) is quite similar to the conclusion made in the framework of the Lund model [4] but has different dynamical origin rooted in the mechanism of the spontaneous breaking of chiral symmetry.

In the region of rather high transverse momenta $p_\perp > \Lambda_\chi$, the effect of this shift will be reduced to the phase factor in impact parameter representation [15]. Taking into account that the quark matter distribution inside the constituent quark has radius r_Q and making the numerical estimation $k_{\perp s/Q} = L_{s/Q}/r_Q$ we use the following relation on the grounds of considerations given in [15]:

$$I_-^{hQ}(s,b,\xi) = \sin[\pm L_{s/Q}] I_+^{hQ}(s,b,\xi). \tag{15}$$

Note that the sign is determined by the direction of rotation of quark-antiquark pairs inside the constituent quark and since the value of orbital angular momentum of $\bar{s}s$ quarks in the constituent quark Q is proportional to the magnitude of its polarization and mean orbital momentum of quarks in the constituent quark, we can rewrite this relation in the form

$$I_-^{hQ}(s,b,\xi) = \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle] I_+^{hQ}(s,b,\xi), \tag{16}$$

where $\mathcal{P}_Q(x)$ is the polarization of the constituent quark Q which is arising due to multiple scattering in the mean field and $\langle L_{\{\bar{q}q\}}\rangle$ is the mean value of internal angular momentum inside the constituent quark. Note that we consider the behaviour of polarization in the fragmentation region (where $x_F \simeq x$) and have taken the value of $L_{s/Q}$ to be proportional to $\langle L_{\{\bar{q}q\}}\rangle$.

Thus, in this model the polarization of strange quark is a result of multiple scattering of the parent constituent quark, a correlation between the polarization of the strange quark and the polarization of the constituent quark and local compensation of spin and orbital angular momentum of strange quark (cf. Eq. (14)). The nonzero orbital angular momentum leads to the shift in the transverse momentum of s–quark and produced Λ-hyperon. This is the reason for the appearance of the factor $\sin[\pm L_{s/Q}]$ in Eq. (15).

The x–dependencies of the functions $I_+^{sQ}(s,b,\xi)$ and $I_+^{hQ}(s,b,\xi)$ are determined by the distribution of constituent quarks in hadrons and by the structure function of constituent quark respectively [15]:

$$I_+^{sQ}(s,b,\xi) \propto \frac{1}{2}(\omega_{Q/h_1}(x) + \omega_{Q/h_2}(x))\Phi^{sQ}(s,b,p_\perp) \tag{17}$$

and

$$I_+^{hQ}(s,b,\xi) \propto \omega_{s/Q}(x)\Phi^{hQ}(s,b,p_\perp). \tag{18}$$

Taking into account the above relations, we can represent the polarization P in the form:

$$P(s,x,p_\perp) = \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle] W_+^{hQ}(s,\xi)/[W_+^{sQ}(s,\xi) + W_+^{hQ}(s,\xi)], \tag{19}$$

where the functions $W_+^{s,hQ}$ are determined by the interactions at long (s) and short (h) distances:

$$W_+^{s,hQ}(s,\xi) = \int_0^\infty bdb I_+^{s,hQ}(s,b,\xi)/|1 - iU(s,b)|^2.$$

3. Behaviour of Λ–polarization

As has been already noted we consider the simplest case of Λ–hyperon production. In this case spin and polarization of hyperon h_3 is completely determined by the spin and polarization of s-quark from the internal structure of parent constituent quark. The latter acquires its polarization due to multiple scattering in the mean field. This polarization is negative, e.g. in gluon external field it is [6]

$$\mathcal{P}_Q \propto -I\frac{m_Q g^2}{\sqrt{s}}. \tag{20}$$

It could have significant value since the constituent quark in our case has a nonzero mass $m_Q \sim m_h/3$ and intensity of the mean field in the model $I \sim \sqrt{s}$ since it is generated by the quasiparticles whose average number is rising with energy like $\sqrt{s}$ [17]. Note that g in Eq. (20) is the coupling constant of quark interaction with external field.

Thus on the basis of above considerations we take an assumption that the polarization of constituent quark is energy independent and it is approaching the maximal value -1 at $x = 1$. The assumption about maximality of polarization at the constituent level has been made on the basis of recent data of ALEPH collaboration [27] which made such indication in the analysis of Λ_b polarization in e^+e^- interaction.

We also take the simplest possible x–dependence of $\mathcal{P}_Q(x)$, i.e. the linear one:

$$\mathcal{P}_Q(x) = \mathcal{P}_Q^{max} x, \tag{21}$$

where $\mathcal{P}_Q^{max} = -1$.

The behaviour of Λ–polarization in the model has significantly different x and $p_\perp$-dependencies in the regions of small and large transverse momenta $p_\perp \leq \Lambda_\chi$ and $p_\perp \geq \Lambda_\chi$. It is convenient to introduce the ratio

$$R(s,\xi) = \frac{W_+^h(s,\xi)}{W_+^s(s,\xi)} = \frac{2\omega_{s/Q}(x)}{\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x)} r(s,p_\perp),$$

where the function $r(s,p_\perp)$ in its turn is the x–independent ratio

$$r(s,p_\perp) = \frac{\int_0^\infty bdb\Phi^h(s,b,p_\perp)/|1-iU(s,b)|^2}{\int_0^\infty bdb\Phi^s(s,b,p_\perp)/|1-iU(s,b)|^2}.$$

The expression for the polarization can be rewritten in the form

$$P(s,x,p_\perp) = \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle]R(s,x,p_\perp)/[1+R(s,x,p_\perp)]. \tag{22}$$

The function $R(s,x,p_\perp) \gg 1$ at $p_\perp > \Lambda_\chi$ since in this region short distance processes dominate and due to the similar reason $R(s,x,p_\perp) \ll 1$ at $p_\perp \leq \Lambda_\chi$. Thus we have a simple $p_\perp$–independent expression for polarization at $p_\perp > \Lambda_\chi$

$$P(s,x,p_\perp) \simeq \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle] \tag{23}$$

and a more complicated one for the region $p_\perp \leq \Lambda_\chi$

$$P(s,x,p_\perp) \simeq \sin[\mathcal{P}_{\tilde{Q}}(x)\langle L_{\{\bar{q}q\}}\rangle]\frac{2\omega_{s/Q}(x)}{\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x)}r(s,p_\perp). \quad (24)$$

As it is clearly seen from Eq. (24) the polarization at $p_\perp \leq \Lambda_\chi$ has a nontrivial $p_\perp$–dependence. In this region polarization vanishes at small $p_\perp$ and is also suppressed by the factor $2\omega_{s/Q}(x)/(\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x))$, which can be considered as the ratio of sea and valence quark distributions in hadron. The x–dependence of polarization in this kinematical region strongly depends on particular parameterization of these distributions. However this dependence in the region of transverse momenta $p_\perp > \Lambda_\chi$ has a simple form reflecting the corresponding dependence of constituent quark polarization. The curve for polarization at $p_\perp > \Lambda_\chi$ corresponding to the linear dependence of $\mathcal{P}_Q(x)$ is presented in Fig. 1. The value of $\langle L_{\{\bar{q}q\}}\rangle \simeq 0.4$ has been taken [15] on the basis of the analysis [14] of the DIS experimental data. To get agreement with experimental data we take the value of parameter $\alpha = 0.8$. Using the above value of quark angular orbital momentum we obtain a good agreement with the data in the case of linear dependence of constituent quark polarization. Note that here we have assumed that the spin structure of transversely polarized constituent quark is the same as the spin structure of longitudinally polarized constituent quark.

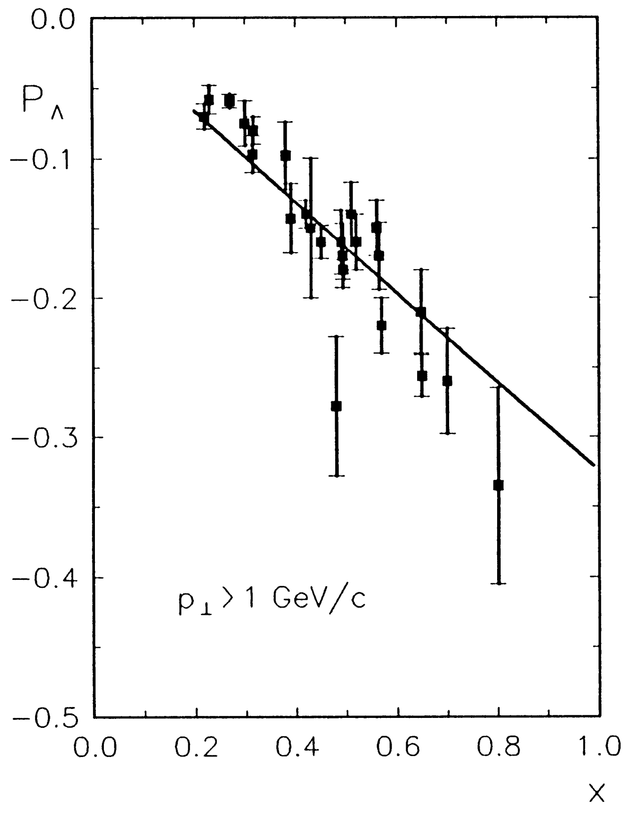

Fig. 1. The x–dependence of Λ–hyperon polarization in the process $pp \to \Lambda X$ at $p_L =$ 400 GeV/c.

The qualitative $p_\perp$ dependence of polarization described above is also in a good agreement with the corresponding experimental data. To describe quantitevely the $p_\perp$ dependence of Λ–polarization, in particular, in the region $p_\perp \leq \Lambda_\chi$ we should choose an explicit parameterization of the cross–section ratio $R(s,x,p_\perp)$ for hard and soft processes. For that purpose we can consider the simplest parameterization of the function R

$$R(s,x,p_\perp) = C(x)\exp(p_\perp/m)/(p_\perp^2+\Lambda_\chi^2)^2. \tag{25}$$

Such parameterization implies a typical behaviour of cross–sections of soft (exponential) and hard (power-like) processes. We take $m = 0.2$ GeV which sets the scale of soft interactions at 1 fm and $\Lambda_\chi = 1$ GeV/c. As an example we consider data at $x = 0.44$ which cover a wide range of $p_\perp$'s. The magnitude of $C(x)$ at the above value of x is chosen to be 0.2 to get an agreement with the experimental data. The corresponding curve and experimental data are given in Fig. 2 and as can be easily seen an agreement with the experiment is good.

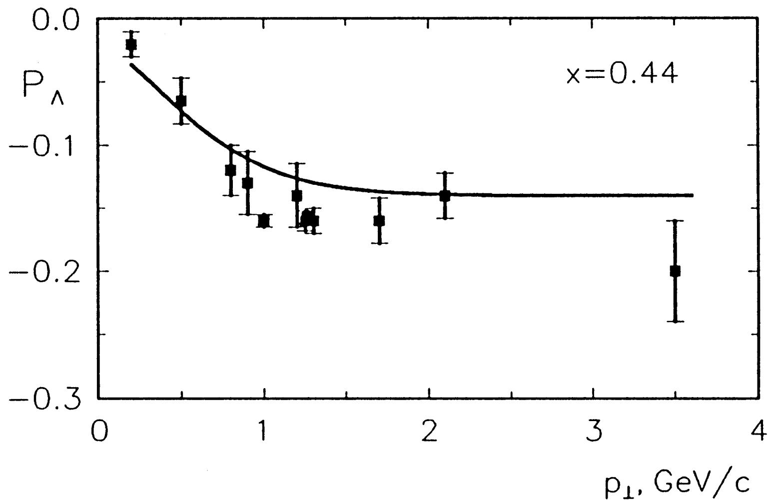

Fig. 2. The $p_\perp$–dependence of Λ–hyperon polarization in the process $pp \to \Lambda X$ at $p_L =$ 400 GeV/c.

Conclusion and discussion

Now we summarize the main results of the considered model:

- polarization of Λ – hyperons arises as a result of the internal structure of the constituent quark and its multiple scattering in the mean field. It is proportional to the orbital angular momentum of strange quarks initially confined in the constituent quark;
- sign of polarization and its value are proportional to polarization of the constituent quark gained due to the multiple scattering in the mean field.

The main role in the model belongs to the orbital angular momentum of $\bar{q}q$–pairs inside the constituent quark while constituent quarks themselves have very slow (if at all) orbital motion and may be described approximately by S-state of the hadron wave function. The observed $p_\perp$–dependence of Λ–hyperon polarization in inclusive processes seems to confirm such conclusions, since it appears to show up beyond $p_\perp > 1$ GeV/c, i.e. the scale where the internal structure of a constituent quark can be probed. Note, that short–distance interaction in this approach observes coherent rotation of correlated $\bar{q}q$–pairs inside the constituent quark but not gas of free partons.

We have considered the simplest case of Λ–hyperon polarization. As to the whole problem, the case of hyperon polarization is extremely complicated and we have not attempted to account for many reactions and a lot of questions remained unanswered. However, few comments on other reactions and the underlying mechanism we could make. First, we would like to note that the experimental data show that the proton polarization in inclusive process $pp \to pX$ is zero. This fact can be easily understood in the model. Indeed, multiple scattering of constituent quarks in the mean field has a lower probability as compared to single scattering. Single scattering does not polarize quarks and protons appear unpolarized in the final state since single scattering is dominant in this process. On the other hand, multiple scattering, excitation and decay of constituent quarks are correlated mechanisms, that is the reason of Λ–hyperon polarization in the model. Of course, $\bar{s}$-quarks will be also produced polarized, but contrary to s-quark, which can easily recombine with constituent quarks of parent protons to produce Λ, $\bar{s}$-quark has no such possibility and should pick up virtual massive quarks generated at the condensate interaction. Since the polarization of produced $\bar{\Lambda}$–hyperons in the process $pp \to \bar{\Lambda}X$ is almost zero we should conclude that the latter mechanism implies strong depolarization dynamics. Thus we have to suppose different mechanisms of Λ and $\bar{\Lambda}$ formation at the final state. Those mechanisms have comparable strength at $x = 0$, but $\bar{\Lambda}$-production has to be suppressed at large x in agreement with the experimental data [1]. To describe a very different behaviour of polarization in other hyperon production it seems that we need a very detailed knowledge of fragmentation dynamics [3] which is unattainable at the moment.

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